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## Description

### Pulse-Tube Refrigerator

#### Field of the invention

The present invention relates to a pulse-tube refrigerator, especially to the pulse-tube refrigerator equipped with a pressure-vibration generator that generates pressure vibration by heat.

#### Background of the invention

A pulse-tube refrigerator consists of a pulse tube, a cool storage unit connected to the low-temperature side of the pulse tube, and a compressor connected to the high-temperature side of the cool storage unit. The pulse-tube refrigerator dispenses with moving parts at the low-temperature side. A pulse-tube refrigerator with a motor-driven compressor generates pressure vibration in the pulse tube by switching open and close alternately a pair of high-pressure and low-pressure valves that are settled between the compressor and the cool storage unit. The basic-type pulse-tube refrigerator by Gifford utilizes a surface heat-pumping effect. An orifice-type pulse-tube refrigerator has a buffer (reservoir tank) connected through the orifice to the high-temperature side of the pulse tube. In this type, the cooling effect comes from the phase difference between the pressure vibration in the pulse tube and the displacement of the imaginary gas piston that is formed in the pulse tube. A double-inlet type connects the flow path between the orifice and the pulse tube to the flow path between the cool storage unit and the compressor with a bypass-flow path that has the other orifice.

With respect to heat engines such as Stirling engine, Figure 9 shows energy flow patterns from heat energy to gas pressure energy in an energy conversion device using a heat storage unit, whose boundary conditions at both ends are varied. In these patterns, (b) of an ideal condition and (c) of rather a realistic condition do not require input work at the low-temperature side of the heat storage unit, although require large sweep volume at the low-temperature side. Referring to Figure 10, a former orifice-type pulse-tube refrigerator is explained. The pulse-tube refrigerator has a pulse tube, a cool storage unit connected to the low-temperature side of the pulse tube, and a buffer tank. A compressor is connected to the high-temperature side (ambient temperature side) of the cool storage unit. A cold station of very low temperature is formed at the part between the pulse tube and the cool storage unit. The cool storage unit consists of

multiplied circle mesh plates of knitted copper wires settled in a metal cylinder, further filled with lead spheres if necessary. Supposing a 'gas piston' drawn with the dotted line in the pulse tube may easily explain the principle of the operation. The name 'gas piston' comes from the expansion-compression operation like a piston made of a rigid body, actually made of the existing gas in the pulse tube. Consider changes of the energy flow brought by the gas passing through the orifice driven by the pressure vibration. When the pressure in the pulse tube is high, isenthalpic inflow to the buffer is accompanied with the falling pressure and raises entropy. When the pressure in the tube is low, isenthalpic outflow from the buffer is accompanied with the falling pressure and raises entropy as well. Accordingly, as far as the vibration continues, entropy continues to increase and the work is continuously absorbed or consumed at the orifice. Note that the average over one cycle of enthalpy flow through the orifice is zero. As a result, a constant work passes through the pulse tube and the gas piston operates like an expansion unit, which causes a temperature drop at the junction of the pulse tube and the cool storage unit and operates as a refrigerator. The explanation above shows that the mechanism of refrigeration is different from the basic-type pulse-tube refrigerator, and is rather in line with GM cycle or Stirling cycle cooling mechanisms.

An orifice-type pulse-tube refrigerator is in principle free from the limitation by the critical temperature slope and may reach very low temperature that basic pulse-tube refrigerator could not achieve. However the efficiency of this type is questionable. Since all the expansion work is converted to heat, the energy cannot be collected, the orifice type is not suitable for a large refrigerator system. In comparison with GM cycle or Stirling cycle cooling systems, the enthalpy flow passing through the cool storage unit is larger which results in lower cooling efficiency and requires a larger cool storage unit.

The ideal cool storage unit has configuration with infinite specific heat and infinite surface area for heat transmission in a finite space and with thermal conductivity low for axis direction of flow and high for radius direction. For example, if the temperatures of the gasses that flow in the both ends are 300 K and 30 K respectively and the cool storage unit keeps a constant temperature slope, inflow at 300 K flows out at 30 K and inflow at 30 K flows out at 300 K. This means that the gas has no thermal vibration at any position with the flow axis.

On the other hand, the most popular type of actual cool storage units consists of multi-layered metal fine mesh punch in a circle shape settled in a thin stainless cylinder and is far from the ideal. This causes net cooling amount loss from an enthalpy flow as a result of thermal vibration of the gas. The enthalpy flow is denoted  $\langle H \rangle$  by one-cycle circular integration of temperature times flow volume times low-pressure specific heat

of the flow. In order to improve the efficiency of the cool storage unit i.e. to reduce  $\langle H \rangle$ , no other choice than reducing the flow is left. However, reducing the flow means reducing the work. Therefore, importance is how the work per unit flow volume should be increased.

Since the basic-type pulse tube is supposed to use an ideal cool storage unit, the enthalpy flow  $\langle H \rangle_R$  in the cool storage unit is zero. The suffix R with the enthalpy flow denotes in the cool storage unit, and P does in the pulse tube. Figure 10 shows how the efficiency loss of the cool storage unit relates to the actual cooling volume loss. Firstly consider the energy flow in the pulse tube and find that quite different from the basic-type pulse tube, there is absolutely no right-hand-direction heat flux  $\langle Q \rangle_P$  that is the base for cooling function. If the inner wall of the pulse tube is completely heat insulating, no heat flux occurs and  $\langle Q \rangle_P = 0$ , and accordingly equation  $\langle W \rangle_P = \langle H \rangle_P$  stands up, as a matter of fact, rather non-zero left-hand-side direction  $\langle Q \rangle_P$  exists. Nevertheless, the orifice-type outperforms the basic type in reaching temperature since the work absorbed by the orifice is much more than the directly transmitted work through the surface of the pulse tube. In summery, although the surface heat-pumping effect is limited by the compression ratio, the orifice type may increase the volume of absorbing work by controlling the flow volume with degree of orifice open, even though the compression ratio is low. Since the work flow decreases under condition that enthalpy flow through the orifice is zero, entropy increases. The increased entropy is radiated as heat in the heat exchanger and the work is converted to heat. On the other hand, Figure 10 shows that the actual cooling volume is  $\langle H \rangle_P$  passing through the pulse tube after subtracting  $\langle H \rangle_P$  that passes through the cool storage unit. The reason why the reaching temperature exists for the refrigerator is that while  $\langle H \rangle_P$  decreases and  $\langle H \rangle_R$  increases as temperature falls down and refrigerating volume  $Q$  finally becomes zero as in equation  $\langle H \rangle_P - \langle H \rangle_R = 0$  under condition of constant input. Accordingly, in order to lower the reaching temperature, it is important to reduce  $\langle H \rangle_R$  by reducing the flow volume under condition of constant work flowing through the pulse tube.

Figure 11 shows a pressure vibration generator proposed in Japanese Patent Application No. 2002-179141, wherein heat-input portion is heated to generate self-excitation vibration in a work transmission tube. The work is amplified with a heat exchanger when the resonator is exited and the work is put into the heat exchanger. The work is transmitted to the work-transmission tube and is put out to the outlet portion. The output work may be more than the input work. A part of the output work may be used as energy to drive the cylinder. Just heating may continuously drive the pressure-vibration generator.

The pulse-tube refrigerator disclosed in Japanese Patent Laid-Open No. (Tokkai Hei) 11-182958 actualized a compact-size pulse-tube refrigerator by truncating the length of the resonance tube of a heat-driven compressor. A self-excitation vibration of the operation gas is generated by heating/cooling the operation gas enclosed in the resonance tube of the heat-driven compressor. The fluid such as hydrogen in the enclosure is cooled to the liquid state by effects of pressure amplitude of the operation gas from the heat-driven compressor upon the pulse tube and the cool storage unit of the refrigerator body. The length of the resonance tube may be truncated by applying a mixture of helium and another rare gas, especially xenon gas.

However, former pulse-tube refrigerator has drawbacks such as large vibration and electric noise if a motor drives the compressor. A compressor with Stirling cycle or the like has a drawback of a large-size resonance tube. Although the heat-driven compressor of the pulse-tube refrigerator cited in the Patent Reference 1 cannot solve these problems mentioned above.

The present invention aims to solve the problems above and to implement a compact pulse-tube refrigerator free from vibration and electric noise.

#### **Summary of the invention**

In order to solve the above mentioned problems, the present invention has configuration of a pulse-tube refrigerator comprising a pulse tube, a cool storage unit connected to the low-temperature side of the pulse tube, a vibration generator connected to the high-temperature side of the cool storage unit, and a reservoir with an orifice connected to the high-temperature side of the pulse tube, and said vibration generator consists of a heat-driven tube equipped with a heat-storage unit, a heating heat exchanger, a radiation heat exchanger, and a work transmission tube, of a phase shifter connected to an outlet portion of the heat-driven tube, and of a heat-driven pressure-wave generator equipped with a return path to connect the other portion of the phase shifter and the inlet end of the heat-driven tube. The configuration of the present invention enabled to implement a compact pulse-tube refrigerator free from vibration and noise. In other words, applying a solid displacer for the resonator and the phase shifter of the vibration generator and disposing them in facing opposite made the device compact and reduced vibration. The heat-driven pressure-wave generator with a resonator tube by the former arts was inevitably large since a small-size resonator does not resonate. A rather small-size resonator tube of former arts presented very low efficiency from the friction between the operation gas and the surface of the tube and was not suitable for actual use. By using a resonator and a phase shifter of the solid

displacer, a compact and efficient heat-driven pressure-wave generator can be implemented. From the similar reason, arranging a resonator and a phase shifter of the solid displacer at the heat-absorber side enables to implement a compact and efficient pulse-tube refrigerator.

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### **Brief description of the drawings**

Figure 1 shows a schematic diagram of the heat-driven pressure-wave generator for the pulse-tube refrigerator in the first embodiment of the present invention,

Figure 2 shows a schematic diagram of the heat-driven pressure-wave generator for the pulse-tube refrigerator in the second embodiment of the present invention,

Figure 3 shows a schematic diagram of the heat-driven pressure-wave generator for the pulse-tube refrigerator in the third embodiment of the present invention,

Figure 4 shows a schematic diagram of the heat-driven pressure-wave generator for the pulse-tube refrigerator in the fourth embodiment of the present invention,

Figure 5 shows a schematic diagram of the resonator for the pulse-tube refrigerator in the fifth embodiment of the present invention,

Figure 6 shows a schematic diagram of the phase shifter for the pulse-tube refrigerator in the sixth embodiment of the present invention,

Figure 7 shows a schematic diagram of the phase shifter with leakage for the pulse-tube refrigerator in the seventh embodiment of the present invention,

Figure 8 shows operation experiment results of the heat-driven pressure-wave generator for the pulse-tube refrigerator in the third and the fourth embodiments of the present invention

Figure 9 shows energy-flux patterns of the heat-driven pressure-wave generator,

Figure 10 shows an energy-flow pattern of a pulse-tube refrigerator by the former arts,

Figure 11 shows a schematic diagram of the heat-driven pressure-wave generator for the pulse-tube refrigerator in the former arts.

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### **Detailed description of the best embodiments**

The best embodiments of the present invention are precisely explained referring to the Figures 1 through 8 in the following.

The first embodiment of the present invention

The first embodiment of the present invention is a pulse-tube refrigerator driven by a heat-driven pressure-wave generator equipped with a heat-driven tube, a phase

shifter, and a return path.

Figure 1 shows the schematic diagram for the pulse-tube refrigerator in the first embodiment of the present invention, wherein the pulse-tube refrigerator 1 is an orifice-type pulse-tube refrigerator that has a pulse tube, a cool storage unit connected to the low-temperature side of the pulse tube, a vibration generator connected to the high-temperature side of the cool storage unit, and a reservoir with the orifice connected to the high-temperature side of the pulse tube. Although omitted in the figure, these are the same as in Figure 10. The heat storage unit 2 is a means to form an isothermal space that has a constant thermal slope, which is called “regenerator”. The heating heat exchanger 3 is a means to supply heat to the high-temperature side of the heat storage unit 2. The radiation heat exchanger 4 is a means to cool the low-temperature side of the heat storage unit 2 down to an ambient temperature. The work-transmission tube 5 is a heat-insulating space and is the tube that transmits work with the pressure wave of the operation gas. The return path 6 is a tube that returns work from the phase shifter 7 to the heat storage unit 2. The phase shifter 7 is a means that delays the phase of the pressure wave of the operation gas with a piston that freely reciprocates in the cylinder. The radiation heat exchanger 4a is a means to cool the work-output side of the work-transmission tube 5 down to an ambient temperature. The heat transmission tube 5 consists of the radiation heat exchanger 4, the heat storage unit 2, the heating heat exchanger 3, and the work transmission tube 5. The heat-driven tube is a device that forms a constant thermal slope in the heat storage unit 2 and amplifies the work of the pressure wave of the operation gas by heating the high-temperature side and cooling the low-temperature side respectively of the heat storage device 2. The heat driven pressure-wave generator consists of the heat-driven tube, the return path 6, and the phase shifter 7.

Here is explained the above configured pulse-tube refrigerator in the first embodiment of the present invention. The phase shifter 7 (Displacer) arranged in bilateral symmetry vibrates symmetrically and excites the operation gas. As a result, there occurs a heat flux that flows from the heating heat exchanger 3 that is heated up to temperature  $T_h$  toward the radiation heat exchanger 4 that is cooled down to temperature  $T_a$ , which causes pressure vibration in the system. This pressure vibration has a certain phase difference with the operation gas displacement and the phase difference becomes the work flow. The energy of the work flow is produced from the heat energy that is taken into the system and a part of which is converted to the work energy. This is proved by the fact that the exhausted heat energy is less than the heat energy taken into the system.

The work flows from the radiation heat exchanger 4 at temperature  $T_a$  toward the heating heat exchanger 3 at temperature  $T_h$ . In other significant words, the work flows against the direction that the heat flows in. The work flow is amplified when it flows through the heat exchanger 2. A part of the amplified work flow is supplied to the radiation heat exchanger 4 at temperature  $T_a$  through the phase shifter 7 (displacer) and the return path 6. The rest of the work is supplied as heat source to the pulse-tube refrigerator 1. At the first stage of this explanation, it was supposed that the vibration of the phase shifter 7 (displacer) is excited. However, the excitation work does not need to be necessarily supplied externally since a self-excitation vibration runs with the work left for the pulse-tube refrigerator 1 after the necessary work is consumed for continuously running the phase shifter 7 (displacer), if the difference between the heating temperature  $T_h$  and the radiation temperature  $T_a$  is large enough.

A part of the work put out of the work-transmission tube 5 is returned to the phase shifter 7 (displacer), and it drives the vibration of the piston in the cylinder. The returned work is converted to a pressure wave that has a different phase with the input pressure wave in the phase shifter 7 (displacer) and fed back to the low-temperature side of the heat storage unit 2. The work fed-back is amplified in the heat storage unit 2 and is transmitted to the work transmission tube 5, and is put out as a traveling wave. The heat-driven tube functions as an amplifier that amplifies the input work and put it out. A part of the output work is again returned to the phase shifter 7 (displacer), and this cycle continuously generates the pressure wave. This heat-driven pressure-wave generator may be applied to an inertance-type pulse-tube refrigerator, or to an electric generator and the like as well.

As explained above, the first embodiment of the present invention consists of the pulse-tube refrigerator specifically driven by the heat-driven pressure-wave generator comprising the heat-driven tube, the phase shifter, and the return path, so that the cooling efficiency is raised with the simple configuration. Accordingly, a compact pulse-tube refrigerator free from vibration and electrical noise can be implemented.

The second embodiment of the present invention

The second embodiment of the present invention is a pulse-tube refrigerator driven by a heat-driven pressure-wave generator that is equipped with a heat-driven tube, a resonator, a phase shifter, and a return path. The heat-driven pressure-wave generator is a Stirling-engine type. Figure 2 shows a diagram of the pulse-tube refrigerator in the second embodiment of the present invention. In Figure 2, the resonator 8 is a gas-spring resonator disposed at the work-output side of the heat-driven tube. The rest of the

configuration is the same as in the first embodiment of the present invention. The basic configuration of this pulse-tube refrigerator is the same as the pulse-tube refrigerator in the former arts shown in Figure 11. The significant difference is that the piston in the phase shifter can freely reciprocate. The heat-driven pressure-wave generator consists of the heat-driven tube, the return path 6, the phase shifter 7, and the resonator 8.

Here is explained an operation of the pulse-tube refrigerator of the second embodiment of the present invention as configured above. After the heating heat exchanger 3 is sufficiently heated, a self-excitation vibration occurs in the work transmission tube 5, and the resonator 8 resonates with this self-excitation vibration with a certain phase shift. A standing wave is generated in the resonator 8 connected to the outlet port of the heat-driven tube, by resonance of the pressure wave of the operation gas. No output work can be taken out of the pressure wave in the resonator 8 since this pressure wave is a standing wave. The work exchange against the resonator 8 evens out in zero over one cycle. The amplitude of the pressure wave of the operation gas traveling in the heat-driven tube is increased, and the amplified work in the heat-driven tube is put out to the pulse-tube refrigerator 1. The work generated in the heat storage unit 2 flows against the direction that the heat flows to. The operation of the phase shifter 7 is the same as in the first embodiment.

This heat-driven pressure-wave generator is a gas-driven self-excitation Stirling engine. The state of the energy flux in the Stirling-cycle engine is as shown in Figure 9a. Heat  $Q_{in}$  is supplied from the high-temperature side of the heat storage unit 2, and is taken away as heat  $Q_{out}$  from the low-temperature side of the heat storage unit 2. The phase shifter 7 is used as an acoustic inertance in the return path. The phase shifter 8 and the resonator 8 are disposed symmetrically to reduce the mechanical vibration. In order to support the piston at a floating state, a bending bearing is used. The diameter of the piston is 52 mm, and the moving mass is 1.85 kg. The heat storage unit 2 is 52 mm in diameter, 57 mm in length, and is filled with screens of 200 meshes. The gap between the piston and the cylinder is about 15  $\mu$ m. Heating temperature is 580 K, mean pressure is 1.5 MPa, excitation frequency is 24.5 Hz, and the minimum amplifying gain is 1.57. The excitation frequency is higher than 23.5 Hz of the piston's resonance frequency. This heat-driven pressure-wave generator may be applied to an inertance-type pulse-tube refrigerator or a generator and the like as well.

As explained above, the second embodiment of the present invention consists of the pulse-tube refrigerator specifically driven by the heat-driven pressure-wave generator comprising the heat-driven tube, the phase shifter, and the return path, so that the cooling efficiency is raised with the simple configuration. Accordingly, a compact

pulse-tube refrigerator free from vibration and electrical noise can be implemented.

The third embodiment of the present invention

The third embodiment of the present invention is a pulse-tube refrigerator driven  
 5 by a heat-driven pressure-wave generator that is equipped with a heat-driven tube and a resonator. The heat-driven pressure-wave generator is a standing-wave type. Figure 3 is a schematic diagram that shows the configuration of the pulse-tube refrigerator in the third embodiment of the present invention. In Figure 3, a heat storage unit 2 is a means to form an isothermal space that has a constant thermal slope. A heating heat exchanger  
 10 3 is a means to supply heat to the high-temperature side of the heat storage unit 2. A radiation heat exchanger 4 is a means to cool the low-temperature side of the heat storage unit 2 down to an ambient temperature. A high-temperature buffer 16 is a tube where the pressure wave is reflected to excite the standing wave in the heat-driven tube. The heat-driven tube consists of the heat storage unit 2, the heating heat exchanger 3,  
 15 the radiation heat exchanger 4, and the high-temperature buffer 16. A resonator 8 is a gas spring resonator disposed at the junction of the heat-driven tube and the pulse-tube refrigerator 1. The heat-driven pressure-wave generator consists of the heat-driven tube and the resonator 8. Here is explained the operation of the pulse-tube refrigerator in the third embodiment of the present invention as configured above. A standing wave is  
 20 generated while the pressure wave of the operation gas resonates in the resonator 8. For the gas displacement of the standing wave, the closed tube-end of the high-temperature buffer 16 becomes the node and the connecting junction part of the resonator 8 becomes the loop. After the amplitude of the pressure wave of the operation gas traveling in the heat-driven tube is increased, the amplified work in the heat-driven tube is put out to the  
 25 pulse-tube refrigerator 1. The work exchange against the resonator 8 evens out in zero over one cycle. This heat-driven pressure-wave generator is a standing-wave-type acoustic heat engine. The heat storage unit 2 uses a coarse mesh called 'stack'. In this heat-driven tube, the work flows in the same direction as the heat flows in, contrary to the first and second embodiments. Energy flows as shown in Figure 9d. Work by the  
 30 pressure wave comes in from the low-temperature-side of the heat-driven tube, reflected by the high-temperature buffer 16, amplified with the heat storage unit 2, and goes out of the low-temperature side of the heat-driven tube. Thus, the low-temperature side of the heat-driven tube is the input/output port of the work. Although the length of the heat-driven tube is short, amplitude of the standing wave is increased with the resonator  
 35 8, efficiency of the pressure-wave generator can be high. This heat-driven pressure-wave generator may be applied to an inertance-type pulse-tube refrigerator and

an electric generator and the like as well.

As described above, the pulse-tube refrigerator in the third embodiment of the present invention is configured to be driven by the heat-driven pressure-wave generator equipped with the heat-driven tube and the resonator, a compact pulse-tube refrigerator free from vibration and electric noise may be implemented and the simple configuration increases the cooling efficiency.

The fourth embodiment of the present invention

The fourth embodiment of the present invention is a pulse-tube refrigerator that is driven by a heat-driven pressure-wave generator equipped with a resonator disposed at the opposite side to the outlet port of the heat-driven tube.

Figure 4 is a schematic diagram that shows the configuration of the pulse-tube refrigerator in the fourth embodiment of the present invention. In Figure 4, the pulse-tube refrigerator 1 is an orifice-type pulse-tube refrigerator. Heat storage unit 2 is a means that configures an isothermal space with a constant thermal slope. Heating heat exchanger 3 is a means that supplies heat to the high-temperature side of the heat storage unit 2. Radiation heat exchanger 4 is a means that cools the low-temperature side of the heat storage 2 down to an ambient temperature. Heat transmission tube 5 is a heat-insulation-tube space that transmits work with the pressure wave of the operation gas. Radiation heat exchanger 4a is a means that cools the work-output side of the work transmission tube 5 down to an ambient temperature. The heat-driven tube consists of the radiation heat exchanger 4, the heat storage unit 2, the heating heat exchanger 3, and the heat transmission tube 5. The device of heat-driven tube, by heating the high-temperature side and cooling the low-temperature side of the heat storage unit 2, forms a constant thermal slope in the heat storage unit 2, and amplifies the work in the pressure wave of the operation gas. Resonator 8 is a gas-spring resonator disposed at the opposite side of the junction of the heat-driven tube and the pulse-tube refrigerator 1. The heat-driven pressure-wave generator consists of the heat-driven tube and the resonator 8.

Here is explained the operation of the fourth embodiment of the present invention as configured above. A pair of resonators 8 (displacer) is attached in bilateral symmetry to the side of radiation heat exchanger 4 at temperature  $T_a$ . A part of the heat flux from the heating heat exchanger 3 at temperature  $T_h$  is converted to a work flow. A further part of the heat flux is taken out of the side of the radiation heat exchanger 4 at temperature  $T_a$  to excite the resonators 8 (displacer). The rest of the work is taken out of the side of the heating heat exchanger 3 at temperature  $T_h$  and is supplied to the

pulse-tube refrigerator 1 through the work-transmission tube 5. Since no feedback loop is formed, there is no worry of instability from infinite cyclic flows.

Standing waves are generated in the resonator 8 by resonance of the pressure waves in the operation gas. Amplitude of the pressure wave in the operation gas traveling in the heat-driven tube is increased and the work amplified in the heat-driven tube is put out to the pulse-tube refrigerator 1. The work exchange against the resonator 8 evens out in zero over one cycle. An experiment with the heat-driven pressure-wave generator presented an oscillation at 31.5 Hz as the resonant frequency with Helium as the operation gas. A pressure ratio 1.1 was obtained at 2.3 MPa of mean pressure that is appropriate to excite the pulse-tube refrigerator. The heating temperature  $T_h$  was 723 K and the cooling temperature was 290 K. Once the pressure vibration occurred, the vibration was sustained until the heating temperature was lowered down to less than 450 K. These experimental results are shown in Figure 8. This heat-driven pressure-wave generator is applied to an inertance-type pulse-tube refrigerator and an electric generator and the like as well.

As described above, the pulse-tube refrigerator in the fourth embodiment of the present invention is configured to be driven by the heat-driven pressure-wave generator equipped with the resonators at both the outlet port and the opposite port of the heat-driven tube, a compact pulse-tube refrigerator free from vibration and electric noise may be implemented and the simple configuration increases the cooling efficiency.

The fifth embodiment of the present invention

The fifth embodiment of the present invention is a pulse-tube refrigerator comprising a gas-spring resonator between the pulse tube and the orifice.

Figure 5 shows the schematic diagram of the configuration of the pulse-tube refrigerator in the fifth embodiment of the present invention. In Figure 5, the resonator 8a consists of a reciprocating piston and a spring of the enclosed gas. The reservoir 13 is a buffer tank that reserves the operation gas in. The orifice 14 is an open path that let the operation gas go through with friction. The rest of the configuration is the same as in the fourth embodiment.

Here is explained the operation of the fifth embodiment of the present invention as configured above. Generally, as a phase-shift controlling device of an efficient pulse-tube refrigerator, 'inertance-type phase-shift controlling device' is used wherein a long tube called 'inertance tube' and a reservoir tank are connected in tandem. However, this device does not present good efficiency if applied to a compact pulse-tube refrigerator, because it requires a small diameter for the long tube and

consequently increases the pressure loss in the vibration of the gas and at the same time decreases the mass of the gas in the tube. As the result, the ideal resonance condition no longer holds good.

On the other hand, an application of the controlling device with a solid piston and an orifice makes the ideal resonance condition hold good even if the refrigerator is downsized as required. The term of 'ideal resonance condition' means that the phase shift of the gas disposition to the pressure wave is held at more than  $90^\circ$ . Recent progress in micro-mechanics technologies made manufacturing a very small-size piston easier, and made the implementation of the device more realistic. The phase-shift controlling device in this system is important to make the pulse-tube refrigerator compact.

The resonator 8a between the pulse tube 15 and the orifice 14 makes even a short pulse-tube resonate. Since the loop of the vibration is on the resonator 8, the operation gas is exchanged with the orifice 14 at high amplitude. Thus, a compact and efficient phase-controlling device may be implemented. The type of the pressure-wave generator is not the matter.

As described above, the fifth embodiment of the present invention is a pulse-tube refrigerator comprising a gas-spring resonator disposed between the pulse tube and the orifice, a compact and efficient pulse-tube refrigerator free from vibration and electrical noise may be implemented. The simple configuration can raise the cooling efficiency.

The sixth embodiment of the present invention

The sixth embodiment of the present invention is a pulse-tube refrigerator comprising a phase shifter disposed between the pulse tube and the orifice.

Figure 6 shows a schematic diagram that presents the configuration of the pulse-tube refrigerator in the sixth embodiment of the present invention. In Figure 6, the phase shifter 7 is a means to retard the traveling phase of the operation gas. The rest of the configuration is the same as in the fourth embodiment of the present invention.

Here is explained the operation of the pulse-tube refrigerator as configured above in the sixth embodiment of the present invention. The phase shifter 7 disposed between the pulse tube 15 and the orifice 14 retards the shifting phase of the operation gas and can raise cooling efficiency. In comparison with the case of orifice 14 alone, the phase shifter 7 increases the phase shift of the gas displacement against the pressure wave and raises cooling efficiency. While the phase shift is provided 0 without the orifice 14, it becomes  $90^\circ$  with the orifice 14. Further addition of the phase shifter 7

increases the phase shift to around  $110^\circ$ . Parameters of the phase shifter 7 may be designed according to the purposes, and the optimum operation is obtained. Any type of the pressure-wave generator to excite the pulse-tube refrigerator may be applied.

As described above, the sixth embodiment of the present invention is a pulse-tube refrigerator comprising the phase shifter disposed between the pulse tube and the orifice, a compact and efficient pulse-tube refrigerator that is free from vibration and electrical noise may be implemented. This simple configuration can raise the cooling efficiency.

The seventh embodiment of the present invention

The seventh embodiment of the present invention is a pulse-tube refrigerator comprising a phase shifter with leakage disposed between the pulse tube and the reservoir.

Figure 7 shows a schematic diagram that presents the configuration of the pulse-tube refrigerator in the seventh embodiment of the present invention. In Figure 7, the phase shifter with leakage 12 is a displacer that has a gap between the cylinder and the piston that the operation gas passes through. There is no orifice.

Here is explained the operation of the pulse-tube refrigerator as configured above in the seventh embodiment of the present invention. The phase shifter with leakage 12 disposed between the pulse tube 15 and the reservoir 13 functions as a displacer and an orifice as well, and it operates almost the same as in the sixth embodiment of the present invention. Although the phase shifter and the orifice are connected in tandem in the sixth embodiment of the present invention, they are regarded as connected parallel in the present embodiment. Using the gap between the cylinder and the piston of the phase shifter 12 as an orifice dispenses with the orifice particularly, and enables compact implementation of the device. Any type of the pressure-wave generator may be applied.

As described above, the seventh embodiment of the present invention is a pulse-tube refrigerator comprising the phase shifter with leakage disposed between the pulse tube and the reservoir, a means to absorb the work can be made up in this simple configuration.

#### Applicability to industry

As explained above, it is obvious with the present invention that a compact pulse-tube refrigerator free from vibration and noise may be implemented since the pulse-tube refrigerator comprises a pulse tube, a cool storage unit connected to the

low-temperature side of the pulse tube, and a vibration generator equipped with a reservoir with an orifice connected to the high-temperature side of the pulse tube, under configuration that this vibration generator is a heat-driven pressure-wave generator consisting of a heat-driven tube, a phase shifter whose one end is connected to the outlet  
5 port of the heat-driven tube, and a return path that connects the other end of the phase shifter to the inlet port of the heat-driven tube, wherein the heat-driven tube consists of a heat storage unit, a heating heat exchanger, a radiation heat exchanger, and a work transmission tube.

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